VOLUME 78 SEPARATE No. D-79

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

MAY, 1952

DISCUSSION OF STAGE PREDICTIONS FOR FLOOD CONTROL OPERATIONS

(Published in July, 1951)

By Robert Buehler and W. S. Hoehl, and Ralph E. King

WATERWAYS DIVISION

Copyright 1952 by the AMERICAN SOCIETY OF CIVIL ENGINEERS
Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N.Y.

PRICE $0.50 PER COPY

V620.6
A512p

GUIDEPOST FOR TECHNICAL READERS

"Proceedings-Separates" of value or significance to readers in various fields are here listed, for convenience, in terms of the Society's Technical Divisions. Where there seems to be an overlapping of interest between Divisions, the same Separate number may appear under more than one item.

Technical Division	*Proceedings-Separate Number*
Air Transport	42, 43, 48, 52, 60, 93, 94, 95, 100, 103, 104, 108, 121, 130 (Discussion: D-XXVIII, D-7, D-16, D-18, D-23, D-43)
City Planning	58, 60, 62, 64, 93, 94. 99, 101, 104, 105, 115, 131 (Discussion: D-16, D-23, D-43, D-60, D-62, D-65)
Construction	43, 50, 55, 71, 92, 94, 103, 108, 109, 113, 117, 121, 126, 130, 132 (Discussion: D-3, D-8, D-17, D-23, D-36, D-40, D-71)
Engineering Mechanics	41, 49, 51, 54, 56, 59, 61, 88, 89, 96, 116, 122, 124, 125, 126, 127, 128, 129 (Discussion: D-5, D-XXIII, D-XXV, D-18, D-24, D-33, D-34 D-49, D-54, D-61)
Highway	43, 44, 48, 58, 70, 100, 105, 108, 113, 120, 121, 130 (Discussion: D-XXVIII, D-7, D-13, D-16, D-23, D-60)
Hydraulics	50, 55, 56, 57, 70, 71, 78, 79, 80, 83, 86, 92, 96, 106, 107, 110, 111, 112, 113, 116, 120, 123, 130 (Discussion: D-XXVII, D-9, D-11, D-19, D-28, D-29, D-56, D-70, D-71, D-79)
Irrigation and Drainage	46, 47, 48, 55, 56, 57, 67, 70, 71, 87, 88, 90, 91, 96, 97, 98, 99, 102, 106, 109, 110, 111, 112, 114, 117, 118, 120, 129, 130 (Discussion: D-XXIII, D-3, D-7, D-11, D-17, D-19, D-25-K, D-29, D-30, D-38, D-40, D-44, D-47, D-57, D 70, D-71, D-80)
Power	48, 55, 56, 69, 71, 88, 96, 103, 106, 109, 110, 117, 118, 120, 129, 130 (Discussion: D-XXIII, D-2, D-3, D-7, D-11, D-17, D-19, D-25-K, D-30, D-38, D-40, D-44, D-70, D-71, D-79)
Sanitary Engineering	55, 56, 87, 91, 96, 106, 111. 118, 130 (Discussion: D-10, D-29, D-37, D-56, D-60, D-70, D-79, D-80)
Soil Mechanics and Foundations	43, 44, 48, 94, 102, 103, 106, 108, 109, 115, 130 (Discussion: D-4, D-XXVIII, D-7, D-43, D-44, D-56)
Structural	42, 49, 51, 53, 54, 59, 61, 66, 89, 100, 103, 109, 113, 116, 117, 119, 121, 122, 123, 124, 125, 126, 127, 128, 129, 132 (Discussion: D-32, D-33, D-34, D-37, D-39, D-42, D-49, D-51, D-53, D-54, D-59, D-61, D-66, D-72)
Surveying and Mapping	50, 52, 55, 60, 63, 65, 68, 121 (Discussion: D-60, D-65)
Waterways	41, 44, 45, 50, 56, 57, 70, 71, 96, 107, 112, 113, 115, 120, 123, 130 (Discussion: D-8, D-9, D-19, D-27, D-28, D-56, D-70, D-71, D-79, D-80)

A constant effort is made to supply technical material to Society members, over the entire range of possible interest. Insofar as your specialty may be covered inadequately in the foregoing list, this fact is a gage of the need for your help toward improvement. Those who are planning papers for submission to "Proceedings-Separates" will expedite Division and Committee action measurably by first studying the ASCE "Guide for Development of Proceedings-Separates" as to style, content, and format. For a copy of this Manual, address the Manager, Technical Publications, ASCE, 33 W. 39th Street, New York 18, N. Y.

The Society is not responsible for any statement made or opinion expressed in its publications

Published at Prince and Lemon Streets, Lancaster, Pa., by the American Society of Civil Engineers. Editorial and General Offices at 33 West Thirty-ninth Street, New York 18, N. Y. Reprints from this publication may be made on condition that the full title of paper, name of author, page reference, and date of publication by the Society are given.

DISCUSSION

ROBERT BUEHLER,[8] ASSOC. M. ASCE AND W. S. HOEHL[9].—In the paragraph preceeding "Conclusions," Mr. King states: "Throughout the critical season very close cooperation is maintained with the TVA***"

Routing methods similar to those of the Stage Prediction Section of the Mississippi River Commission are used during a flood by the Flood Control Branch of the TVA as an aid to project operation. Such methods are also used (as rapidly as preliminary basic inflows and outflows can be received) to determine Cairo stages for natural Tennessee River flows as a measure of the effectiveness of the TVA system. After the flood is over, when provisional basic inflows and outflows are available, more refined estimates are prepared. The preliminary flows are usually instantaneous morning rates received daily by teletype as the flood is in progress. The provisional flows at most locations are the midnight-to-midnight average daily discharges which are scheduled for publication later in the appropriate yearly pamphlets of the United States Geological Survey (USGS) or the Mississippi River Commission. Slight variations in procedure allow for the difference in time of observation for the two classes of data.

In addition to studies that show the effect, at Cairo, of actual TVA reservoir operation, the Flood Control Branch uses routing procedures to compute the effect of theoretical reservoir regulation. Ideal operation is one such type which, if there is a sufficient volume of water, makes full use of all storage up to gatetop levels to reduce Cairo to its lowest level crest stage. It is an optimum operation against which the effectiveness of other regulations can be measured.

As does the Mississippi River Commission, the TVA prepares storage curves and Cairo rating curves for each flood from the actual data collected or forecast as the flood progresses. During a flood TVA also extends these curves somewhat beyond the data when they are serving to help guide reservoir operations. They are also extended after the flood peak has passed to reach the higher stages and flows that would have resulted without the TVA system. The departure of average rating curves and routing curves from somewhat scattered data usually results in little indicated error in computed Cairo stage. Alternate trial positions of curves with respect to data to test this effect have resulted in Cairo stage differences of only a few tenths of a foot.

The main purpose of this discussion is to demonstrate that in at least one application of the routing method to Cairo, appreciable differences in the results are caused by using different inflow stations. Contributing to Cairo floods are flows from the Mississippi and Ohio Rivers. Discharges are obtained on the Mississippi River at Thebes, a short distance above Cairo,

NOTE.—This paper by Ralph E. King was published in July, 1951, as *Proceedings-Separate No. 79*. The numbering of footnotes and tables in this Separate is a continuation of the consecutive numbering used in the original paper.

[8] Civ. Engr. V, Hydr., TVA, Knoxville, Tenn.

[9] Civ. Engr. III, Hydr., TVA, Knoxville, Tenn.

and below major tributaries on the Ohio River at Metropolis, Ill. Metropolis flows are composed of contributions from the Tennessee and Cumberland Rivers and from the Ohio River proper above these tributaries. Suitable discharge stations on these streams, respectively, are Kentucky Dam, Dover (or Smithland), and Golconda. In addition there are unmeasured local contributions between gages.

Applications of the TVA routing procedure to Cairo embodies changing the contribution from the Tennessee River only. This may involve the use of natural Tennessee River flows instead of actual regulated flows to determine the effect of regulation, or it may involve hypothetical regulated flows. In any event, TVA routing is in effect the passage of altered Tennessee River flows through storage to learn the effect at Cairo.

Storage and routing curves prepared with Dover, Golconda, Kentucky Dam, and Thebes as inflow stations include the natural valley storage below these locations down to Cairo, all lumped together. When the curves then are used in a computation which seeks only to show the effect of modifying Tennessee River flows, these modified flows are being routed through storage lying along streams in which Tennessee waters actually do not travel. Specifically, these modified flows are being routed through combined storage which incorrectly includes portions along the Mississippi River from Thebes to Cairo, along the Cumberland River below Dover, and along the Ohio River from Golconda to the mouth of the Tennessee River. The incorrect inclusions minimize the computed effect at Cairo of altering Tennessee River flows.

Changing the inflow stations to Metropolis on the Ohio River and to Thebes on the Mississippi River is not a complete remedy, but has been found to give results which are believed to be better. When these inflow stations are used, the effect of modifying Tennessee River flows is introduced by altering Metropolis flows by the extent of the change at Kentucky Dam. This method correctly includes the valley storage below Metropolis, incorrectly excludes storage along the Tennessee and Ohio Rivers between Kentucky Dam and Metropolis, and incorrectly includes valley storage on the Mississippi River below Thebes. These two inaccuracies cause opposite effects. The omission of Tennessee and Ohio River valley storage exaggerates the computed effect at Cairo of altering Tennessee River flows. The inclusion of Mississippi River valley storage minimizes the effect. The influence that dominates may depend on the relative size of contributions in the basic flood used to prepare storage curves. If the Mississippi River at Thebes is unusually high compared to other contributions, a large volume of natural valley storage may be built into the combined storage curve and this minimizing influence may dominate; or, unusually large Ohio or Tennessee flows used to prepare the combined storage curves may cause the exaggerating influence to dominate.

It may be argued that a more correct appraisal could be made by routing altered Tennessee River flows from Kentucky Dam to the mouth, combining these with Ohio River flows routed to the same point, and then routing these combined flows to Cairo. Here the Ohio flows would be combined with the flows routed down the Mississippi River from Thebes. Although this appraisal

would be more correct, the task would involve so much time and study that, with present methods, it is prohibitive.

To determine which of the two stated inflow station locations would give the more nearly correct computed Cairo stage, approximate corrections for storage errors, excepting on the Mississippi below Thebes, have been prepared for the January, 1950, flood. Data were not conveniently available to make this Mississippi River correction. All comparisons have been computed using identical inflows and outflows for any given selection of inflow stations, and using a variation of the routing procedure described by Mr. King for the river reach immediately above Cairo. This variation of method first was checked to be sure it had no influence on results.

For the Golconda-Dover-Kentucky Dam-Thebes selection of inflow stations the routed Cairo crest stage, if there had been no Tennessee River regulation, was 56.7 ft. When adjustments were applied to correct for having routed altered Tennessee River flows through natural storage on the Cumberland and upper Ohio Rivers this Cairo crest was increased to 57.5.

For the Metropolis-Thebes selection of inflow stations the routed Cairo crest stage, if there had been no Tennessee River regulation, was 57.4 ft. Corrections for having ignored natural Tennessee River storage below Kentucky Dam, and some Ohio River natural storage, reduced this Cairo crest slightly to 57.3 ft.

These results show that the selection of inflow stations in the January, 1950, flood had a substantial effect on the estimated Cairo crest stage when no regulation was assumed in the Tennessee River. In this 1950 flood, errors that are evidently present when using Golconda-Dover-Kentucky Dam-Thebes inflows are greater in their effect on Cairo than are the errors present when Metropolis-Thebes inflows are used. It does not necessarily follow that this will be true in all floods. Uncorrected error for storage along the Mississippi River from Thebes to Cairo is present in both comparisons.

Because the system using inflows at Golconda-Dover-Kentucky Dam-Thebes appears to have a chance of error always in one direction, it seems preferable to use the other selection, Metropolis-Thebes, in which erroneous influences are opposite, and have at least some chance of canceling each other.

It should be mentioned that corrections for storage errors are quite involved and would not be prepared except on an experimental basis or in case of unusually important Cairo floods.

RALPH E. KING[10].—The writer is fully in accord with the argument advanced by Messrs. Buehler and Hoehl that a more correct appraisal of the effects of modifying flows from the Tennessee River could be made if the flows from the individual rivers could be routed separately to the points of confluence and then combined. He also agrees with their contention that the time and study which would be required make this method of computation impractical.

Since routing of the separate flows is not feasible, the selection of inflow stations on several streams which contribute to the total flow at Cairo, becomes of primary importance. The choice of inflow stations to be used

[10] Engr., Mississippi River Commission, Vicksburg, Miss.

during the progress of a flood, for the purpose of predicting future stages at stations downstream, is limited by the availability of such stations and by the degree of accuracy with which flows at the different stations can be predicted.

For predicting flood stages at Cairo, the choice of inflow stations must of necessity be either the Golconda-Smithland-Kentucky Dam-Thebes combination, as used by the Mississippi River Commission office, or the Metropolis-Thebes combination as suggested by Messrs. Buehler and Hoehl. From a cursory inspection the Metropolis-Thebes selection would appear to be the better of the two because of the more simplified routing procedure required. If this selection of stations is used for predicting flood stages, the error of excluding natural storage along the Tennessee and Ohio Rivers, between Kentucky Dam and Metropolis, is not made since the total Ohio River contribution is estimated for the Metropolis station. However, experience with past floods, during which both groups of inflow stations have been used, has indicated that the predictions of flood flows at Golconda are less subject to error than are similar predictions for Metropolis. Because the minor amount of additional computations required is more than compensated for by the increased accuracy of the Cairo forecasts, the Stage Prediction Section of the Mississippi River Commission prefers to use the Golconda-Smithland-Kentucky Dam-Thebes combination of inflow stations for making predictions during the occurrence of a flood.

Although determination of the effect on Cairo stages of modifying flows from the Tennessee River was not discussed in the paper, the writer is grateful to Messrs. Buehler and Hoehl for discussing this application of the basic method. Any value which the original paper might possess will be considerably enhanced by the inclusion of another practical application of the same routing method.

Introducing the effect of modifying Tennessee River flows by altering Metropolis flows to the extent of the change at Kentucky Dam has the following disadvantages:

a. Valley storage along the Ohio and Tennessee rivers between Kentucky Dam and Metropolis is incorrectly excluded;

b. Valley storage along the Ohio and its tributaries from the mouth of the Tennessee River upstream to the limit of the backwater effect produced by the flows from the Tennessee River is incorrectly excluded; and

c. Variations in Ohio River flows above the mouth of the Tennessee River, caused by modification of flows from Kentucky Dam, are not included.

The disastrous flood on the Missouri river in 1951 produced a crest stage of 40.6 ft at Cairo on July 28. The stage tendencies at stations on the lower Ohio River from July 2 to the date of the Cairo crest, except for minor fluctuations, are shown in Table 3.

Flow from the upper Mississippi River (which includes the flood flow from the Missouri River) caused valley storage to accumulate along the Ohio River from Cairo to a point upstream from Golconda. Although the flow from the upper Mississippi River does not pass through this reach, the successful routing of this flood requires the inclusion of valley storage along the Ohio River below the selected inflow station which could be either Golconda or

Metropolis. Further confirmation of the fact that the accumulation of valley storage along the Ohio River was caused by the floods from the upper Mississippi River is given by an inspection of the releases from Kentucky Dam during the same period. The average daily flow from Kentucky Dam, which was 52,000

TABLE 3.—STAGE TENDENCIES OBSERVED IN THE LOWER OHIO RIVER

Gaging station	Station mile[a]	Stage tendency	Total change in stage (ft)
Cairo, Ill.	2.2	Rising	+5.5
Dam 53, near Mound City, Ill.	19.1	Rising	+5.0
Dam 52, near Metropolis, Ill.	42.8	Rising	+4.5
Paducah, Ky., near the mouth of the Tennessee River	47.2	Rising	+4.7
Dam 51, near Golconda, Ill.	78.6	Rising	+0.8
Dam 50, near Fords Ferry, Ky.	104.9	Falling	−3.5

[a] Mile above the confluence of the Ohio River and the Mississippi River.

cu ft per sec on July 2, 1951, increased to 73,000 cu ft per sec on July 4, decreased at a fairly uniform rate to 20,000 cu ft per sec on July 21, and then gradually increased to 45,000 cu ft per sec on July 28. Because valley storage along the Ohio River below Golconda was increasing from July 4 to July 21 (the period in which outflow from Kentucky Dam was decreasing) flow from the Tennessee River is eliminated as a possible contributing factor.

Since flows from the upper Mississippi River affect valley storage along the Ohio River, it follows that flows from the Ohio River will produce a similar effect on the upper Mississippi River above Cairo and that flows from the Tennessee River can affect valley storage on the Ohio River above the mouth of the Tennessee River. For this reason the writer is unable to agree with the contention of Messrs. Buehler and Hoehl that the selection of Metropolis as the inflow station on the Ohio River incorrectly includes valley storage on the Mississippi River below Thebes, or that the selection of Golconda results in the incorrect inclusions of the Mississippi River below Thebes, the Cumberland River below Smithland (or Dover), and the Ohio River from Golconda to the mouth of the Tennessee River.

Studies of the effect on Cario stages of modifying the Tennessee River flows during the January, 1950, flood were made by the writer using both Metropolis and Golconda as inflow stations. The use of the Metropolis-Thebes selection resulted in a routed crest stage at Cairo of 57.4 ft, assuming that there had been no Tennessee River regulation. For the Golconda-Smithland-Kentucky Dam-Thebes selection the routed Cairo crest stage, if there had been no Tennessee River regulation, was 57.1 ft.

Because the routing that used the Metropolis-Thebes selection of inflow stations did not allow for either the inclusion of valley storage on the Ohio River from Metropolis to the upstream limit of the backwater influence of the Tennessee River, or for the decrease in Ohio River flow which would result from an increase in the flow from the Tennessee River, the routed stage of 57.4 ft at Cairo is higher than the stage that would have been routed if the proper corrections were feasible.

The Cairo stage of 57.1 ft, which was routed using the Golconda-Smithland-Kentucky Dam-Thebes selection of stations, is subject to error because no reductions, for the effect of increased flow from the Tennessee River, were made in the flows at Golconda and because the valley storage on the Ohio River, from the mouth of the Tennessee River to Golconda, would be slightly increased by the backwater effect of the increased flow from the Tennessee River. Correction of the routing method to allow for these factors would probably result in a slightly different routed crest stage at Cairo. The word "probably" is used because any reduction in flow at Golconda would tend to reduce the valley storage in the reach, and any raise in stages caused by flow from the Tennessee River would tend to increase the valley storage in the reach. Since these two corrections have opposite effects, it is doubtful whether their incorporation in the routing procedure would result in any appreciable difference in the routed Cairo stages.

Based on the foregoing analysis of the various factors that affect the combining and routing of flood flows from the various streams involved, in order to determine stages at Cairo, it is believed that the use of the Golconda-Smithland-Kentucky Dam-Thebes combination of inflow stations is preferable to the Metropolis-Thebes selection, for either predicting stages during a flood or determining the effect of modifying flows from the Tennessee River. This belief is further strengthened by the results of model tests conducted by the Waterways Experiment Station at Vicksburg. These tests (which were made in 1947 for the purpose of determining the effects on Cairo crest stages of modifying Tennessee River flows for the 1945, 1946, and 1947 floods) gave results which were in substantial agreement with the results obtained from routings that used the Golconda-Smithland-Kentucky Dam-Thebes combination of inflow stations.